

CLIMATE CHANGE VULNERABILITY ASSESSMENT OF RARE PLANTS  
IN CALIFORNIA

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ABSTRACT

We assessed the vulnerability to climate change of 156 rare plant species. The species were selected from the 1625 rare species in California to comprise eight rarity types, classified according to range size, population size, and habitat specificity. For each of the 156 species, we first assigned a climate change vulnerability score using life history attributes and species distribution models, as specified by the Climate Change Vulnerability Index (CCVI) of NatureServe. The resulting CCVI scores were extremely vulnerable ( $n = 2$ ), highly vulnerable ( $n = 40$ ), moderately vulnerable ( $n = 57$ ), presumed stable ( $n = 32$ ), increase likely ( $n = 16$ ), and insufficient evidence ( $n = 9$ ). *Piperia yadonii* Rand, Morgan & Ackerman and *Mimulus purpureus* A. L. Grant were the species scored as extremely vulnerable. There was no correlation of the CCVI scores with rarity type, suggesting that climate change vulnerability cannot be inferred by simple categorizations based on geographic range and habitat preference. Second, we conducted a follow-up species distribution model sensitivity analysis that showed that the modeling results were highly dependent upon both model algorithm and choice of predictor variables. However, 60 of the 156 species were predicted to have declines in climatic suitability, regardless of modeling technique. Third, as an independent assessment of vulnerability, we calculated the topographic complexity around known occurrences of each species. Species in topographically dissected landscapes may be less vulnerable to climate change because they can find suitable climates locally as climate changes. We found that topographic complexity varied substantially, even within a single CCVI score level, and therefore provides unique information on vulnerability. Our results can be used to guide monitoring, management, and conservation plans for rare plant species.

Key Words: California, climate change, NatureServe, rare plants, vulnerability.

Climate change may negatively impact the flora of California, a biodiversity hotspot with over 2000 endemic plant species (Myers et al. 2000). A changing climate may reduce and extirpate populations (Pounds et al. 2006), cause species to migrate north and upslope (Parmesan 1996; Kelly and Goulder 2008; Loarie et al. 2009), advance flowering times, promote species invasion, increase disturbance (e.g., fire), and cause community reorganization (Walther et al. 2002; Burkett et al. 2005). Several tools have been developed to identify which species and habitats are most imperiled by the negative impacts of climate change (Schnieder et al. 2007; Williams et al. 2008; Heller and Zavaleta 2009; EPA 2009; Byers and Norris 2011; Glick et al. 2011; Schlesinger et al. 2011), under the assumption that the world will continue to warm in the near term, even if emissions are immediately reduced (IPCC 2007). By identifying species or habitats most at risk from effects of climate change, conservation and management efforts can be targeted to reduce these impacts, such as by protecting existing habitat or through assisted migration (Hunter 2007; McLachlan et al. 2007).

Vulnerability assessments provide a standardized method to assess sensitivity to climate

change that is time-efficient, repeatable, and is directly comparable across species. Investigators can use vulnerability assessments to rank a list of species with regard to their relative expected sensitivity to shifts in climate (Gardali et al. 2012). Most studies are focused upon individual species; however, recent work has also considered the vulnerability of landscapes (Klausmeyer et al. 2011). For example, topographically complex landscapes may provide refugia or paths for movement to more suitable areas under changing temperature and moisture regimes (Hunter et al. 1988; Beier and Brost 2010). Moreover, understanding how regional and local processes interact to create spatial heterogeneity in climate may help predict the direction and rate of climate change (Ackerly et al. 2010). Further, assessments of geophysical diversity (i.e., the number of bedrock types) may be a useful alternative to species-level assessments, since high levels of geological diversity are often associated with habitat heterogeneity and species diversity (Anderson and Ferree 2010).

Species-level vulnerability assessments are typically based on intrinsic life history traits, species distribution models (SDMs), or both. The trait-

based approach identifies and scores species attributes relevant to avoiding or tolerating climate change, such as movement ability (i.e., dispersal rates) or sensitivity to changes in temperature or moisture. The sum of these scores represents the species' overall vulnerability to climate change. Trait-based indices were largely developed with animals as a primary focus. For example, the International Union for Conservation of Nature (IUCN) analyzed the life history, ecology, behavior, physiology, and genetic make-up of "red list" animal species to assess a species vulnerability to climate change (Foden et al. 2009).

A second set of tools used to assess vulnerability to climate change is SDMs (Pearson and Dawson 2003; Loarie et al. 2008; Stralberg et al. 2009). Typically, point occurrence data for a species are used to create a statistical model of climatic suitability using historical (often 30-year-mean) climate data. This model is then used to predict the species' contemporary range, based on a grid of historical climate, and the species' future range, based on a grid of predicted future climate. Finally, the change in predicted range size and the amount of range overlap is calculated. Species with large range reductions and/or low range overlap are considered to be more vulnerable than species with small range reductions and/or high range overlap. However, there are a large number of modeling techniques used to describe climatic suitability, and differences in model algorithms and assumptions can greatly influence the quality of model predictions (Araújo and New 2007).

A leading example of combining species traits and SDMs into a single vulnerability analysis comes from NatureServe (Arlington, VA), a non-profit organization whose mission is to provide the scientific basis for effective conservation action. NatureServe developed the Climate Change Vulnerability Index (CCVI) to serve as a standardized methodology for assessing vulnerability to climate change at the species level (Young et al. 2012). The CCVI consists of a Microsoft Excel document with four main sections: Section A—direct exposure to changing temperature and precipitation; Section B—indirect exposure to climate change, including sea level rise, natural and human barriers, and land impacts from climate mitigation; Section C—sensitivity factors (hereafter referred to as "life history traits"); and Section D—modeled response to climate change.

Our goal was to assess the vulnerability of California rare plant species to climate change and to evaluate the application of the NatureServe CCVI method to rare plants. Rarity is a major feature of California's botanical heritage. The California Native Plant Society (CNPS) Rare Plant Program, which works in coordination with the California Department of Fish and Game's (CDFG) Natural Diversity Database,

recognizes 1625 plant taxa as rare or endangered, as of March 1, 2011. While many of the 1625 taxa are subspecies and varieties, and thus the words "taxa" and "taxon" are appropriate than "species," we use "species" throughout the text for simplicity. There are 26 California Rare Plant Rank 1A—presumed extinct in California; 1132 Rank 1B—rare or endangered in California and elsewhere; and 492 Rank 2—rare or endangered in California, but more common elsewhere (CNPS 2001). These rare species may have narrow ranges, small population sizes, or narrow habitat preferences (or all of the above) for natural or anthropogenic reasons (CNPS 2001). The potential impacts of climate change were not a factor considered by CNPS when assigning rare plant ranks; thus, which of the 1650 species will be most vulnerable to climate change has been largely uninvestigated.

Climate-only SDMs suggest California plants may be in trouble: 66% will experience 80% reductions in range size within a century (Loarie et al. 2008). In addition, plants may be unable to adjust their ranges fast enough to spatially track shifting climates (Loarie et al. 2009). It is possible that rare species may be even more sensitive to climate change, given their limited geographic ranges and small population sizes. Or, perhaps they will be less sensitive to climate change, given their specialized ecologies. These attributes also make it more difficult to accurately model rare species than common species. Given our conservation concerns, it is our hope to create a meaningful vulnerability ranking for rare species and to identify which spatial and life history factors contribute most to that vulnerability.

Due to the large number of rare plants in California, we sought to determine whether the level of climate change vulnerability could be inferred for certain groups of rare plants based on rarity type, life history traits, or biogeographic affinity. Our work can be divided into three complementary parts. First, for a subset of the 1650 rare plants ( $n = 156$ ), we compiled a set of life history attributes and created distribution models to rank vulnerability as specified by the CCVI of NatureServe. Second, we conducted a SDM sensitivity analysis to determine how choice of model algorithm and predictor variables influenced distribution model predictions of habitat suitability in future climates. Third, we calculated an index of vulnerability based on topographic complexity around known occurrences.

## METHODS

### Species Selection

To create a list of focal species that was representative of California rare plant species as a whole, we first classified each of the 1625 species



TABLE 1. TYPES OF RARITY. The types of rarity, modified from Rabinowitz (1981), come from intersecting range size (small or large), population size (small or large), and habitat specificity (habitat specialist or generalist). For each category, the number of species in our sample and an example species is provided. While only seven of the eight groups are “rare,” species with relatively large ranges, large populations, and generalist habitat preferences among our sample are still relatively rare with respect to the average species in the flora. Thus, we used all eight groups for our selection.

| Population size   | Large range                   |                                | Small range                   |                              |
|-------------------|-------------------------------|--------------------------------|-------------------------------|------------------------------|
|                   | Habitat generalist            | Habitat specialist             | Habitat generalist            | Habitat specialist           |
| Large populations | n = 28                        | n = 25                         | n = 24                        | n = 17                       |
|                   | <i>California macrophylla</i> | <i>Streptanthus morrisonii</i> | <i>Mimulus purpureus</i>      | <i>Allium tuolummense</i>    |
| Small populations | n = 24                        | n = 15                         | n = 17                        | n = 6                        |
|                   | <i>Lilium parryi</i>          | <i>Calochortus plummerae</i>   | <i>Taraxacum californicum</i> | <i>Monardella stebbinsii</i> |

into one of the eight types or forms of rarity (Rabinowitz 1981) (Table 1). Following Rabinowitz’s (1981) definitions, only seven of the eight groups are “rare,” because the combination “large range, large population, and habitat generalist” is considered common. However, since our sample pool was made up of only rare species, even the species within this pool with large ranges, large populations, and generalist habitat preferences were rare relative to the average species in the flora. Thus, we sampled across all eight groups to obtain our subset of 156 species (Appendix 1). Nomenclature for these species follows the CNPS Inventory (2001).

We used information from the California Natural Diversity Data Base (CNDDDB) to attribute each species with the three variables required for rarity type classification, as follows: (1) range size—total area of species range based on a minimum convex polygon encompassing mapped occurrences from the CNDDDB; (2) population size—the median population number of individuals, extracted from the comment field of CNDDDB; and (3) habitat specificity—substrate affinity, extracted from the habitat field of CNDDDB. For range size and population size, species were designated as large or small based on their value relative to the median of the distribution of values. We then randomly selected species from each of the eight rarity types (Table 1). Our list of 156 species includes 139 California Rare Plant Rank 1Bs, 13 Rank 2 s, and three Rank 3 s. While rank 3 s are not nominally rare and thus do not contribute to the 1625 described above, we included three of these species to see if they had remarkably different vulnerability scores.

Climate Change Vulnerability Index (CCVI)

*CCVI overview.* The NatureServe CCVI (release 2.01) assesses 24 climate change vulnerability risk factors, placed in four categories: direct exposure, indirect exposure, life history traits, and modeled response. To complete the CCVI, we collected information on the distribution,

natural history, and conservation status of rare species from CDFG, CNPS, and NatureServe. We then conducted a literature review, mapped species distributions, and modeled responses to climate change. Biologists and botanists were consulted to fill data gaps as needed for particular species. Collected data and sources for each species are available online at [www.dfg.ca.gov/biogeodata/](http://www.dfg.ca.gov/biogeodata/).

*CCVI Section A: Direct exposure (two factors).* Direct exposure was scored based on the percentage of the species’ range that falls into NatureServe’s recommended categories of projected changes of temperature or moisture. The temperature change categories (decreasing in severity) were >3.1°C, 2.8–3.1°C, 2.5–2.7°C, 2.2–2.4°C, and <2.2°C; the moisture change categories (decreasing in severity) were <–0.119, –0.097––0.119, –0.074––0.096, –0.051––0.073, –0.028––0.050, and >–0.028. Climate data (Fig. 1a–d) and projections for the year 2080 were derived by The Nature Conservancy and downloaded from their Climate Wizard (Model: Ensemble Average, emission scenario [ES] A2; [www.climatewizard.org](http://www.climatewizard.org)). Temperature change was the predicted change in annual temperature by 2080, calculated over the range of the species in California. Moisture change was the predicted net change in moisture based on the Hamon AET:PET Moisture Metric, calculated over the range of the species in California. Additional climate data was acquired for the modeled response (Section D) and SDM sensitivity analysis (II) from WorldClim, as described below.

*CCVI Section B: Indirect exposure (four factors).* Indirect exposure evaluated landscape configuration factors that may affect the vulnerability of a species to climate change: Exposure to sea level rise, distribution relative to natural barriers, distribution relative to anthropogenic barriers, and predicted impact of land use changes resulting specifically from human responses to climate change. To evaluate these factors, we compared the distribution of the known occurrences of each species with a map of

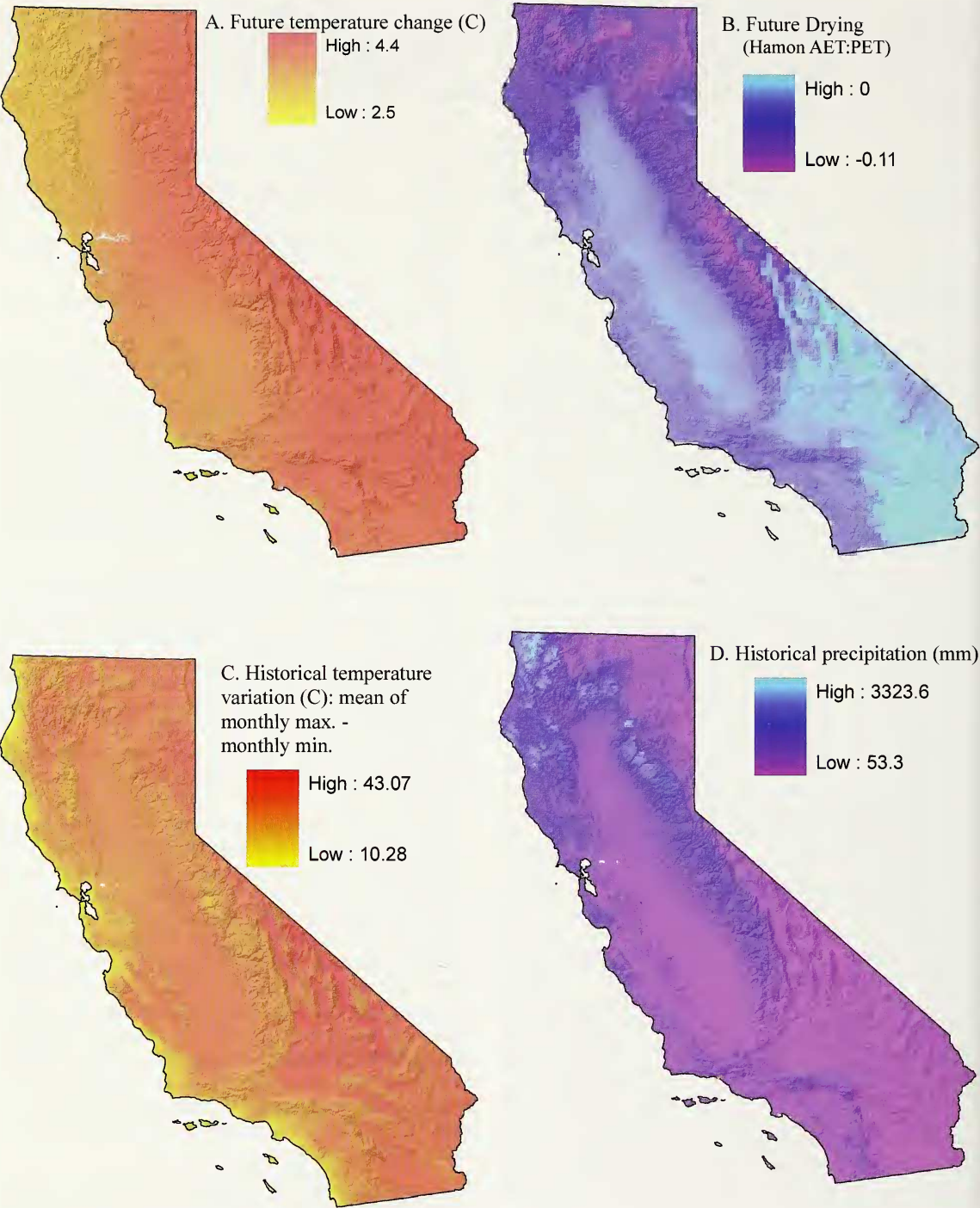


FIG. 1. Map of future temperature change (a), future drying (b), historical temperature variation (c), and historical annual precipitation (d).

predicted sea level rise (Strauss et al. 2012), topographic maps that depicted landscape features, and maps of proposed renewable energy (e.g., solar power stations, wind farms, geothermal wells; California Department of Fish and Game 2011). For sea level rise, the percent of the

species' range occurring in areas subject to sea level rise were placed into five broad categories (decreasing in vulnerability): (1) >90%, (2) 50–90%, (3) 10–49, (4) <10, and (5) predicted increase in extent (intertidal species whose habitat may increase with sea level rise). For barriers,



TABLE 2. LIFE HISTORY TRAITS USED IN DETERMINING CLIMATE CHANGE VULNERABILITY INDEX (CCVI) IN THIS STUDY. Assumptions and data sources are listed for each determining factor.

| Factor                                                     | Assumption                                                                                                | Data source                                                                                                                                                                             |
|------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Dispersal and movements                                    | Lower dispersal ability leads to high vulnerability.                                                      | Dispersal mechanisms from scientific literature and expert opinion.                                                                                                                     |
| Predicted sensitivity to temperature and moisture changes  | Narrow historical climate exposure and special microclimatic preferences leads to high vulnerability.     | Historical temperature and precipitation variation from Climate Wizard. Physiological hydrological niche and physiological thermal niche from scientific literature and expert opinion. |
| Dependence on a specific disturbance regime                | Dependence on a particular disturbance regime leads to high vulnerability.                                | Adaptation and affinity for fire and flood-prone habitats from scientific literature and expert opinion.                                                                                |
| Restriction to uncommon geological features or derivatives | Habitat specialization leads to high vulnerability.                                                       | Substrate affinity from CNDDB. SSURGO soil data from the NRCS.                                                                                                                          |
| Reliance on interspecific interactions                     | Dependence on other species (facilitation, pollinators, and seed dispersers) leads to high vulnerability. | Literature and expert opinion.                                                                                                                                                          |
| Genetics                                                   | Low genetic diversity leads to high vulnerability.                                                        | Not scored for any species due to insufficient information.                                                                                                                             |
| Phenological response                                      | Shorter bloom period leads to high vulnerability.                                                         | CNPS's Rare Plant Inventory bloom-period database.                                                                                                                                      |

each species was placed into one of four categories (decreasing in vulnerability): (1) Barriers completely surround the current distribution, (2) barriers border the current distribution incompletely but will likely impair distributional shifts, (3) barriers border the current distribution incompletely but will be unlikely to impair distribution shifts, and (4) significant barriers do not exist. For renewable energy, each species was placed into one of four categories (decreasing in vulnerability): The likelihood that a species' natural history or range may be (1) very likely to conflict with mitigation-related land-use changes, (2) likely to conflict with land-use changes, (3) likely to benefit from land-use changes, or (4) very likely to benefit from land-use changes.

*CCVI section C: life history traits (16 factors).* The life history traits were grouped into the following categories: dispersal/movement, sensitivity to temperature or moisture, disturbance-dependence, geologic restriction, interspecific interactions, genetic diversity, and phenology (Table 2). Each species was scored by assessing whether its life history traits would be expected to decrease, somewhat decrease, neutral, somewhat increase, increase, or greatly increase its vulnerability to climate change. If information was not available for a particular factor, it was scored as unknown. Guidance on how to rank each factor was provided by NatureServe. Ranks for ten factors in this group were required or the vulnerability index returned a score of "Insufficient Evidence."

*CCVI Section D: Modeled response (two factors).* We modeled the change in range size

and range overlap of predicted future range with predicted current range using the Maxent algorithm, a statistical model that uses machine learning (Phillips et al. 2006; Elith and Leathwick 2009).

The spatial centroid of each CNDDB mapped occurrence record was used. The records of the CNDDB have been carefully curated by the staff of CDFG, yet uncertainty in the exact locations likely remains, contributing an unknown, but likely small, amount of variation to the model results presented here. Another limitation is that occurrences outside of CA are omitted; however, visual examination of the distributions of our focal species suggests that only ~10% have distributions that may cross into Oregon or Baja California, Mexico. We used a dataset acquired from WorldClim (Hijmans et al. 2005) comprising four climate variables (annual temperature, annual precipitation, seasonality of temperature, and seasonality of precipitation) for current conditions (mean 1950–mean 2000) and for future conditions (called "2080," but data are means for 2070–2100; Global Circulation Model [GCM] CGCM3.1, ES A1B) at 1 km<sup>2</sup> resolution. We fit a Maxent model for current conditions and used the resulting model to predict climatic suitability, ranging from 0–1, for both current and future conditions; background points were selected randomly. Maxent was run using the default "auto features" mode, allowing the use of linear, quadratic, product, threshold, and hinge features. These continuous surfaces were then converted to binary (suitable/unsuitable) using a threshold determined as the value that maximizes the kappa, a statistical measure of the agreement

TABLE 3. CLIMATE CHANGE VULNERABILITY INDEX SCORE DESCRIPTIONS.

| Index scores               | Descriptions                                                                                                                                                                                            |
|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Extremely vulnerable (EV)  | Abundance and/or range extent within geographical area assessed extremely likely to substantially decrease or disappear by 2050.                                                                        |
| Highly vulnerable (HV)     | Abundance and/or range extent within geographical area assessed likely to decrease significantly by 2050.                                                                                               |
| Moderately vulnerable (MV) | Abundance and/or range extent within geographical area assessed likely to decrease by 2050.                                                                                                             |
| Presumed stable (PS)       | Available evidence does not suggest that abundance and/or range extent within the geographical area assessed will change (increase/decrease) substantially by 2050. Actual range boundaries may change. |
| Increase likely (IL)       | Available evidence suggests that abundance and/or range extent within geographical area assessed is likely to increase by 2050.                                                                         |
| Insufficient evidence (IE) | Available information about a species' vulnerability is inadequate to calculate an index score.                                                                                                         |

between predictions and observations, and the AUC values were calculated (Cohen 1960; Jiménez-Valverde 2011). Change in range size was calculated as the total area predicted as suitable in the future ( $t_2$ ) minus the total area predicted as suitable in the present ( $t_1$ ), divided by total area predicted as suitable at  $t_1$ . Range overlap was calculated as the total area predicted to be suitable at  $t_1$  and  $t_2$ , divided by the total area predicted as suitable at  $t_1$ . The geographic extent of all models was California. This may overestimate range loss when a species' new range is predicted to be outside of California.

*CCVI risk factor score.* The natural history and distributional information for each species was entered into the CCVI Excel calculator to obtain scores for each species. The output was one of six vulnerability scores: extremely vulnerable (EV), highly vulnerably (HV), moderately vulnerable (MV), presumed stable (PS), increase likely (IL), and insufficient evidence (IE; Table 3). All vulnerability index scores were calculated with and without modeled response to climate change (Section D).

*Statistical analysis of CCVI predictors.* To identify which of the factors were most strongly associated with the resulting vulnerability scores, we evaluated the distribution of risk factor scores against the distribution of CCVI scores across all of our species. Factors that were frequently scored as increasing or decreasing vulnerability should show up as significant predictors of the distribution of CCVI scores, while factors that were infrequently scored as increasing or decreasing vulnerability should not. We converted the CCVI scores and factor ranks to their numeric equivalents, then regressed the CCVI score vs. each of the factors from these sections. We did not test for a relationship of CCVI with dietary versatility, genetic variation, or genetic bottlenecks, because no species were scored for those factors. Tests varied in the number of species included because we did not have information on all life history

traits for all species (i.e., when the factors were marked as unknown). We also compared the CCVI score with California Rare Plant Rank and rarity type using two one-way ANOVAs. Finally, we tested if range size change or range overlap was related to California Rare Plant Rank and rarity type using four one-way ANOVAs.

SDM Sensitivity Analysis

For each of the 156 species, we ran 22 additional SDMs to estimate the sensitivity of range predictions to modeling algorithms and choice of predictor variables. Our 23 models (all run in Maxent unless stated otherwise) were: 1) 19 climate variables (bioclim); 2) four climate variables (described above); 3–14) four climate variables, with different GCM\*ES combinations (GCMs included BCCR-BCM2.0, CSIRO-Mk3.0, INM-CM3.0, and MIROC3.2 [medres]; ESs included A2, AB, and B1); 15) 19 climate variables with soil type; 16) 19 climate variables with soil properties (pH, organic matter, and clay); 17) four climate variables with soil type; 18) four climate variables with soil properties (pH, organic matter, and clay); 19) four climate variables, with a customized geographic extent for each species; 20) four climate variables with an equal number of presences and pseudo-absences; 21) four climate variables, with Random Forest; 22) four climate variables, with random forest, and with a customized geographic extent for each species; 23) four climate variables, with the boosted regression tree model. Soil type data came from the Geologic Map of California (Jennings et al. 2010), which we simplified into seven "soil types" (gabbro, granite, limestone, sandstone, serpentine, shale, and volcanic) and rasterized to 1 km<sup>2</sup> resolution. Soil property data were obtained from the Natural Resources Conservation Service (NRCS) soil survey geographic database (SSURGO) and rasterized to 1 km<sup>2</sup>. The customized geographic extents were determined by intersecting the point occurrence data with the Jepson Ecoregions (Hickman 1993);



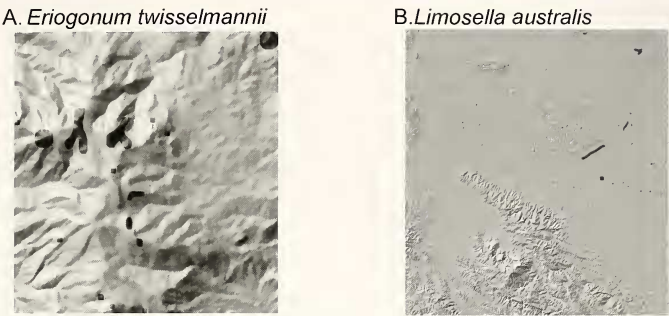


FIG. 2. Illustration of topographic complexity. (a) *Eriogonum twisselmannii* had an anomaly score of  $-0.61$  and a topographic complexity (standard deviation of elevation) of  $27.3$ . (b) *Limosella australis* had an anomaly score of  $-0.64$  and a topographic complexity score of  $0.51$ .

for each species, the predictor raster surfaces were cropped to the shape of the ecoregions that contained the species.

To compare the model predictions, we calculated an “anomaly score” for each species and each model. For a given species, at each known occurrence, an anomaly value was calculated as the predicted suitability in the present ( $t_1$ ) subtracted from the predicted suitability in the future ( $t_2$ ). The mean of the anomaly values across all occurrences was the “anomaly score” for each species. A negative anomaly score meant that suitability in the future was predicted to be lower than current suitability.

There are two main advantages of using an anomaly score to compare model predictions for our SDM sensitivity analysis, rather than using the conventional metrics of change in range size or range overlap. First, the anomaly score can be derived without converting continuous predicted surfaces to binary, the latter of which requires determining a threshold above or below which a particular location is considered suitable or unsuitable. For rare species, it is especially difficult to choose a meaningful threshold, given the limited number of point occurrences available for evaluation of the prediction errors made at various threshold values (Hijmans 2012). Second, anomaly scores are based on climate suitability change only at known occurrences, while range size and overlap consider the entirety of California. Most rare plant species occupy only a small portion of their range where specific habitat requirements are met, and managers are most concerned with how climate suitability will change where the species actually occurs. Evaluating change in suitability over the entire range of the species requires assumptions about habitat occupancy and movement that may not be met by many rare plant species. Furthermore, using the anomaly score meant that predictions were only necessary for known occurrences, making our sensitivity analysis computationally feasible.

We asked if the anomaly score was significantly related to the model type, within species, using a two-way ANOVA. Tukey’s HSD tests were

used for post-hoc means separation by model type. We also examined the relationship of anomaly score and CCVI score using linear regression. Finally, we tested if the median anomaly score of each species was related to California Rare Plant Rank or rarity type using two one-way ANOVAs.

Topographic Complexity Analysis

As an index of “topographic complexity,” we calculated the standard deviation of elevation (resolution =  $30 \times 30$  m) within 100 m of each occurrence, and took the mean of those values per species. Topographic complexity measured at 1000 m was highly correlated with topographic complexity measured at 100 m ( $r = 0.94$ ,  $P < 0.001$ ), so just the 100 m buffer was used. A species in a topographically complex landscape was considered less vulnerable than a species in a topographically homogeneous landscape (Fig. 2). We asked if the topographic complexity score was significantly related to the CCVI score using linear regression. We also tested if the topographic complexity score was related to California Rare Plant Rank or rarity type using two one-way ANOVAs.

RESULTS

Climate Change Vulnerability Index

Of the 156 species assessed, 99 were determined to be vulnerable (extremely vulnerable, highly vulnerable, or moderately vulnerable) to climate change and 48 were determined to be stable or increasing (presumed stable or increase likely). The distribution of final scores was: extremely vulnerable ( $n = 2$ ), highly vulnerable ( $n = 40$ ), moderately vulnerable ( $n = 57$ ), presumed stable ( $n = 32$ ), increase likely ( $n = 16$ ), and insufficient evidence ( $n = 9$ ). *Piperia yadonii* Rand, Morgan & Ackerman and *Mimulus purpureus* A. L. Grant were the species scored as extremely vulnerable. All assessment scores and species attribute data

TABLE 4. TOP FIVE MOST VULNERABLE SPECIES AS DETERMINED BY CLIMATE CHANGE VULNERABILITY INDEX SCORE. For CCVI, IL = increase likely, PS = presumed stable, MV = moderately vulnerable, HV = highly vulnerable, EV = extremely vulnerable, and IE = insufficient evidence. CCVI (without D) is the CCVI score recalculated after excluding the species distribution model results. The global (G) and state (S) rankings are from the California Natural Diversity Data Base; G-rank is the global rank, reflecting global rarity, and S-rank is the state rank, reflecting state rarity. Both indices range from 1 to 5, with 1 being critically imperiled and 5 being secure. California Rare Plant Rank 1B is rare or endangered in California and elsewhere and Rank 2 is rare or endangered in California, but more common elsewhere. Federal listing is the status of the species according to the Endangered Species Act. Section D refers to the modeled response of the CCVI. CCVI index score definitions follow Table 3. \**Limosella australis* may not be native to California.

| Rank                            | Species                                           | CCVI | CCVI        |        |        | California<br>Rare Plant<br>Rank | Federal<br>listing |
|---------------------------------|---------------------------------------------------|------|-------------|--------|--------|----------------------------------|--------------------|
|                                 |                                                   |      | (without D) | G-rank | S-rank |                                  |                    |
| Based on CCVI with Section D    |                                                   |      |             |        |        |                                  |                    |
| 1                               | <i>Piperia yadonii</i> (Orchidaceae)              | EV   | HV          | 5      | 2      | 2                                | None               |
| 2                               | <i>Mimulus purpureus</i> (Phrymaceae)             | EV   | HV          | 2      | 2.2    | 1B                               | None               |
| 3                               | <i>Calliandra eriophylla</i> (Fabaceae)           | HV   | MV          | 5      | 2&3    | 2                                | None               |
| 4                               | <i>Limosella australis*</i><br>(Scrophulariaceae) | HV   | HV          | 4&5    | 2      | 2                                | None               |
| 5                               | <i>Taraxacum californicum</i><br>(Asteraceae)     | HV   | MV          | 2      | 2      | 1B                               | Endangered         |
| Based on CCVI without Section D |                                                   |      |             |        |        |                                  |                    |
| 1                               | <i>Monolopia congdonii</i> (Asteraceae)           | MV   | EV          | 3      | 3      | 1B                               | Endangered         |
| 2                               | <i>Orcuttia viscida</i> (Poaceae)                 | HV   | EV          | 1      | 1      | 1B                               | Endangered         |
| 3                               | <i>Pogogyne abramsii</i> (Lamiaceae)              | MV   | EV          | 1      | 1      | 1B                               | Endangered         |
| 4                               | <i>Symphyotrichum lentum</i><br>(Asteraceae)      | HV   | EV          | 2      | 2      | 1B                               | None               |
| 5                               | <i>Mimulus purpureus</i> (Phrymaceae)             | EV   | HV          | 2      | 2.2    | 1B                               | None               |

are reported in Appendix 1. The top five most vulnerable species, with and without Section D (“modeled response”), are listed in Table 4.

For the 156 species assessed, the final CCVI score was significantly related to just one of the factors that were used to calculate it: anthropogenic barriers (NatureServe factor B2b;  $r^2 = 0.09$ ,  $P < 0.001$ ,  $n = 147$ ). Anthropogenic barriers were determined to limit the migration ability of 99 of the 156 species, and the presence of anthropogenic barriers was significantly related to overall climate change vulnerability. Although not significantly related to overall climate change vulnerability, two factors were found to increase vulnerability for the majority of rare plants assessed: land use change from human response to climate change was found to increase vulnerability for 80 species, and narrow temperature tolerance (“historical thermal niche”) was also found to increase vulnerability for 80 species.

Overall climate change vulnerability was not significantly related to California Rare Plant Rank. For example, final CCVI scores for 1B species were spread rather evenly as highly vulnerable ( $n = 35$ ), moderately vulnerable ( $n = 49$ ), presumed stable ( $n = 30$ ), and increase likely ( $n = 14$ ). In addition, overall climate change vulnerability was not related to rarity type. Similarly, neither change in range size nor range overlap were significantly related to California Rare Plant Rank or rarity type.

SDM Sensitivity Analysis

The anomaly scores statistically differed by species and by model type (species  $P < 0.001$ ; model type  $P < 0.001$ ), where the models with the most positive anomalies (greatest increase in suitability) were those made with Maxent that included soils information, and the models with the most negative anomalies (greatest reduction in suitability) were those made with Random Forest.

The anomaly score and the CCVI score were significantly related ( $r^2 = 0.54$ ,  $P < 0.001$ ), where species scored as vulnerable also had low anomaly scores. This is not surprising, given the CCVI score included modeled response. In fact, the CCVI score calculated after excluding modeled response was not significantly related to the anomaly score. The anomaly score was not significantly related to California Rare Plant Rank or rarity type.

Topographic Complexity Analysis

Topographic complexity and the CCVI score were not significantly related. Topographic complexity was not significantly related to California Rare Plant Rank, but was significantly related to rarity type ( $P < 0.001$ ), where habitat specialists occurred in locations with higher topographic complexity than habitat generalists.



## DISCUSSION

We have three key results: (1) 2/3 of our focal species were scored as vulnerable to climate change, (2) SDM predictions were highly variable, and (3) topographic complexity may provide complementary information on climate change vulnerability.

## Climate Change Vulnerability Index (CCVI)

Ninety-nine of our 156 species (63%) were vulnerable to climate change (scored as moderately vulnerable or worse). We present a list of the top five most vulnerable species (Table 4), an annotated species list (Appendix 1), and all the information we used to make our determinations (CCVI Excel workbooks and species profiles available online; CDFG 2011). We were unable to elucidate strong relationships between species characters and vulnerability. No significant relationship was found between the CCVI vulnerability rank and California Rare Plant Rank, plant rarity type (Rabinowitz 1981), or any species life history trait considered. This suggests that direct exposure to climate change based on projected changes to future temperature and precipitation conditions within a species' range was the strongest driver of vulnerability.

One vulnerability factor from the Indirect Exposure Section (landscape configuration) was significantly (but weakly) related to the CCVI scores: anthropogenic barriers. For 99 of the 156 species, the ability to migrate to track shifting climate will likely be impeded by man-made barriers. This may reflect the fact that many rare species are concentrated in coastal areas, where population density and associated fragmentation are extremely high (e.g., the San Francisco Bay Area and Los Angeles) (Stein et al. 2000). Coastal areas support "naturally rare" plant species that have evolved or survived over time in local refugia because of cool, aseasonal climates and a high level of soil heterogeneity. Other rare plants in coastal areas were once more common and have become "anthropogenically rare" due to high levels of development and habitat loss. Whether naturally or anthropogenically rare, if these species are unable to tolerate new climate conditions and cannot find refuge from novel, intolerable climates locally, the likelihood of dispersing to a more favorable, distant location is expected to be very low given man-made barriers. These species are prime candidates for assisted migration (McLachlan et al. 2007; Richardson et al. 2009; Vitt et al. 2010).

The general inability to predict the CCVI vulnerability scores using the indirect exposure and life-history traits reflects the high importance of direct exposure (projected changes to temperature and moisture within a species' range) in

calculating the overall CCVI score. This is perhaps unsurprising, given that the indirect exposure and life-history traits are weighted by direct exposure in the calculation of the final CCVI score (Young et al. 2012). While this multiplicative approach makes it difficult to identify which risk factors are most important for a group of species, it is the appropriate approach for the CCVI, because a species with zero exposure to climate change should be considered invulnerable even if it has traits that make it sensitive to climate change, and vice versa.

We found the CCVI scores were independent of both California Rare Plant Rank and rarity type. This suggests that the rarest species, such as the California Rare Plant Rank 1B species or habitat specialists with small ranges and small population sizes, are not necessarily the most vulnerable to climate change. We also found no relationship of CCVI scores with other species attribute information, including plant life-cycle duration, plant growth form, and biogeographic affinity (results not shown). This is a desirable result, as it suggests that the CCVI scores contain novel information. This is perhaps the greatest strength of the CCVI: It represents a framework for thinking exclusively about climate change vulnerability. In developing the CCVI, a goal of NatureServe was to create an index that would be as independent as possible from existing rarity ranking indices. We suggest that the CCVI score can be viewed alongside of rarity scores (e.g., California Rare Plant Rank) to identify the most vulnerable *and* rarest species.

## SDM Sensitivity Analysis

Our sensitivity analysis found that SDM predictions were highly variable. The range of anomaly scores per species was very large (Fig. 3), reflecting sensitivities to the choice of predictor variables and model algorithm (i.e., Maxent, Random Forest, and boosted regression trees). Further, for 90 of the 156 species, the *direction* of the anomaly (decreasing suitability or increasing suitability) was even variable (yellow bars of Fig. 3). One of the largest sources of variability in modeled response was the algorithm. In particular, Random Forest always produced the highest anomaly scores. Despite the high variability in anomaly scores, AUC values were uniformly high (mean = 0.988, median = 0.993, range = 0.921–1.00). These high AUC values suggest that all models are equally good, despite the fact that the models make radically different predictions about future climatic suitability. This is unsurprising, as AUC values tend to be inflated for species with narrow distributions, and therefore may not adequately





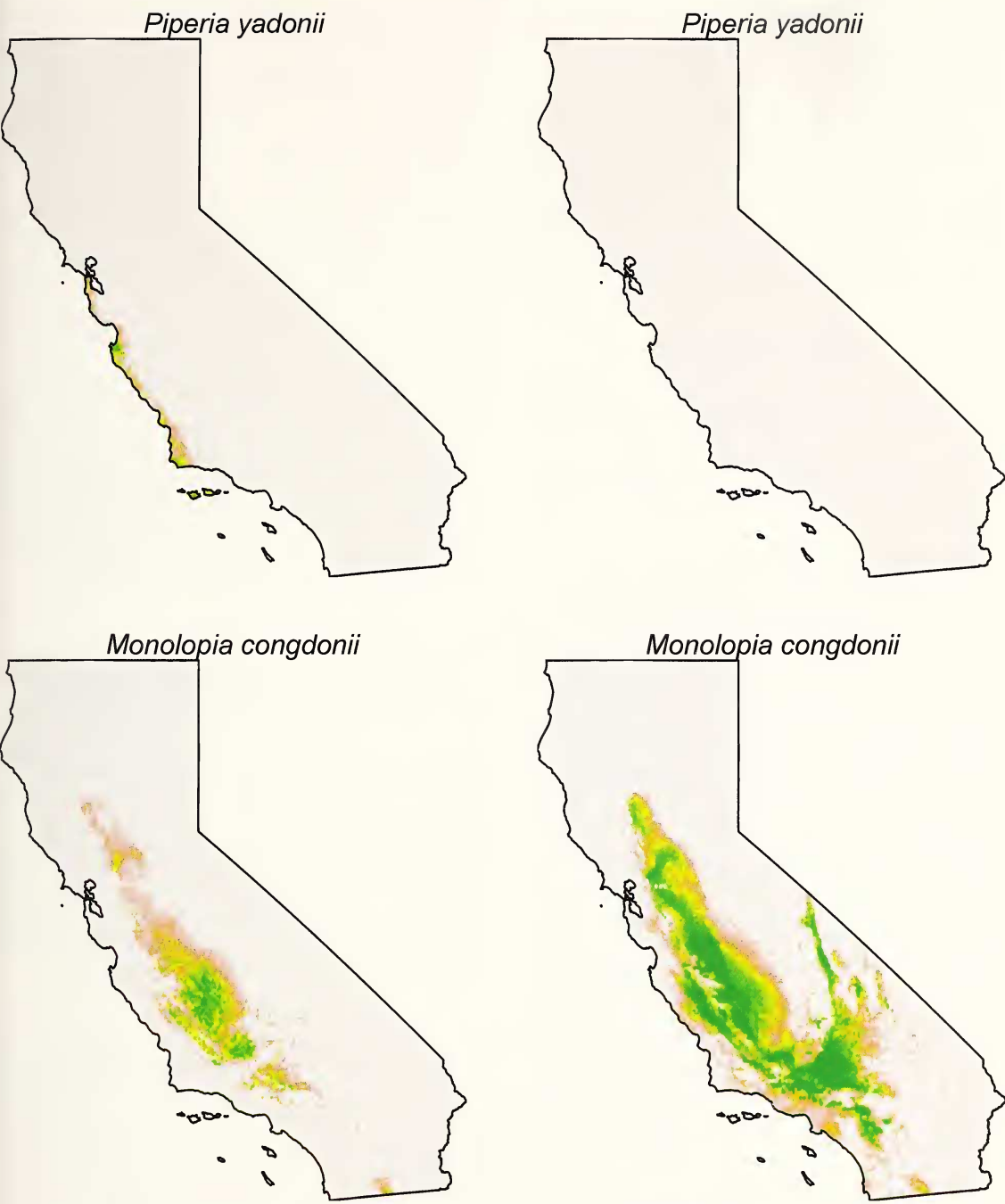


FIG. 4. Maps of the predicted current (left column) and future (right column) ranges for two vulnerable species. For *Piperia yadonii*, the predicted range loss causes the overall CCVI score to increase, from highly vulnerable to extremely vulnerable. For *Monolopia congdonii*, the predicted range gain causes the CCVI score to decrease, from extremely vulnerable to moderately vulnerable.

Thus, we can single out the highly vulnerable species that also have low topographic complexity scores as being especially vulnerable, especially if they have low dispersal ability, with the mechanistic expectation that the local topography will not be sufficient to buffer a species from

region-wide climate change by providing local refugia. An additional benefit is that elevation data is available at higher resolution than climate variables, allowing for finer suitability predictions. Furthermore, topographically homogeneous places have been predicted to have faster

velocities of climate change, at least when compared at the worldwide scale (Loarie et al. 2009). That said, the relationship between local landscape features and climate is complex and is just beginning to be described (Dobrowski 2011). Moreover, the interactions among topography, soils, soil water capacity, and microclimate on plant performance remains poorly described, despite the fact that our observations suggest plants are extremely sensitive to such interactions, at least in California and, more generally, in the mid-latitudes.

### CCVI for Rare Plants

NatureServe's CCVI is an excellent structure and transparent clearinghouse for information regarding climate change vulnerability. To our knowledge, it considers the most exhaustive list of extrinsic and intrinsic factors that may influence vulnerability, and also allows input of model-based results. Further, it is in use by many different groups, allowing for comparison of results. However, we've identified several problems with the CCVI as it applies to plants.

We were able to process only one species per eight-hour workday, a rate far too slow and expensive for most agencies to use for all the listed species in California. Our approach of subsetting a larger list based on rarity type had the advantage of possibly identifying particular combinations of range size, population size, and habitat specialism that cross-walk to climate change vulnerability, thus saving us the need to complete the CCVI for the remaining species. However, we found rarity type had no predictive power for the CCVI scores, and thus a detailed species-level analysis seems necessary to rank species with regards to climate change vulnerability. An alternative or complementary approach is to conduct other types of assessments, including vulnerability of landscape features (topography and connectivity) and habitats. These assessments can be completed relatively easily, and the results are perhaps more reliable, given that the connection of vulnerability scores to landscape features and habitats is less tenuous than the connection of vulnerability scores to species distributions and species ecologies. For example, most conservationists might agree that a well-connected landscape is less vulnerable to climate change than a fragmented landscape, but fewer might agree that a species with three pollinators is less vulnerable to climate change than a species with only one pollinator.

Some attributes that are important to plant vulnerability are missing, including mating system (selfing vs. out-crossing) and pollinator specificity and efficiency. We recommend that different "flavors" of the CCVI be released in the future, at least one for animals and one for

plants. Also, it is nearly impossible to complete the scoring for a given plant species, because information is simply lacking. When information is lacking, the guidelines often recommend scoring the species as neutral, while "unknown" is often the more appropriate score. Also, some of the scoring guidelines are too simplistic. For example, soil endemics are scored as more vulnerable to climate change than soil generalists, while this remains an under-addressed research question (Damschen et al. 2012). A related issue is that soil specificity should be assessed as a natural barrier; currently, it is only considered a life history trait. Finally, while the CCVI accounts for species interactions in a general sense, it does not explicitly take into account invasive species, which have major impacts on California plant diversity. Invasive species can become more virulent or less virulent depending on temperature and precipitation changes, and can greatly affect a species' native habitat. For example, a recent study showed that climate shifts could increase the dominance of exotic species (Sandel and Dangremond 2012).

### CONCLUSIONS

The information produced in our vulnerability assessments will be useful in identifying the most vulnerable rare plant species to climate change, which can then be carefully monitored. Moreover, vulnerability assessments are an excellent way to identify knowledge gaps and to form new hypotheses about species distributions and climatic tolerances. Viewing multiple sources of information together, including the CCVI vulnerability score, rarity ranking, topographic complexity, and a range of SDM results may give a broader picture of the overall vulnerability of a rare plant species to climate change.

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For CCVI (IL = increase likely, PS = presumed stable, MV = moderately vulnerable, EV = highly vulnerable, EV = extremely vulnerable, and IE = insufficient evidence). Positive anomaly = increase in climatic suitability, negative anomaly = decrease in climatic suitability. Topographic complexity is the standard deviation of elevations within 100 m of each occurrence. Range size change = ((future-present)/present). Range overlap is the sum of area predicted to be suitable future *and* present, divided by the sum of area predicted as suitable at present. For rarity type g = geographic range size (l = large, s = small), p = population (l = large, s = small), h = habitat specificity (s = specialist, g = generalist).

| Taxon                                                      | Family         | CCVI<br>(with D) | CCVI<br>(without D) | Anomaly | Topographic<br>complexity | Range size<br>change | Range<br>overlap | Rarity<br>type | CA Rare<br>Plant Rank |
|------------------------------------------------------------|----------------|------------------|---------------------|---------|---------------------------|----------------------|------------------|----------------|-----------------------|
| <i>Abronia alpine</i>                                      | Nyctaginaceae  | IE               | HV                  | NA      | 12.16                     | NA                   | NA               | gspshs         | IB                    |
| <i>Abronia villosa</i> var. <i>aurita</i>                  | Nyctaginaceae  | IE               | MV                  | -0.11   | 5.47                      | 26.6                 | 71.44            | glpshg         | IB                    |
| <i>Agrostis blasdalei</i>                                  | Poaceae        | IE               | MV                  | NA      | 7.93                      | NA                   | NA               | glpshg         | IB                    |
| <i>Allium jepsonii</i>                                     | Alliaceae      | IL               | PS                  | 0.02    | 18.38                     | 816.02               | 98.1             | gspshs         | IB                    |
| <i>Allium munzii</i>                                       | Alliaceae      | PS               | HV                  | -0.18   | 10.34                     | 86.81                | 68.79            | gspshg         | IB                    |
| <i>Allium tuolummense</i>                                  | Alliaceae      | HV               | PS                  | -0.77   | 11.85                     | -99.28               | 0                | gspshs         | IB                    |
| <i>Amorpha californica</i> var. <i>napensis</i>            | Fabaceae       | IL               | PS                  | 0.16    | 16.61                     | 237.29               | 99.44            | glpshg         | IB                    |
| <i>Arctostaphylos klamathensis</i>                         | Ericaceae      | HV               | PS                  | -0.63   | 18.15                     | -100                 | 0                | glplhs         | IB                    |
| <i>Arctostaphylos rainbowensis</i>                         | Ericaceae      | HV               | MV                  | -0.47   | 15.34                     | -76.05               | 19.63            | glpshs         | IB                    |
| <i>Arctostaphylos virginata</i>                            | Ericaceae      | MV               | PS                  | -0.12   | 15.34                     | 2.95                 | 68.31            | gspshg         | IB                    |
| <i>Astragalus brantianii</i>                               | Fabaceae       | IL               | PS                  | 0.28    | 12.07                     | 1762.4               | 99.99            | glplhs         | IB                    |
| <i>Astragalus insularis</i> var. <i>harwoodii</i>          | Fabaceae       | PS               | PS                  | -0.51   | 7.37                      | 46.32                | 49.9             | gspshg         | 2                     |
| <i>Astragalus lentiginosus</i> var. <i>coacheliae</i>      | Fabaceae       | MV               | MV                  | -0.58   | 10.07                     | -45.36               | 6.26             | glpshg         | IB                    |
| <i>Astragalus lentiginosus</i> var. <i>kernensis</i>       | Fabaceae       | MV               | MV                  | -0.21   | 16.85                     | 321.35               | 26.02            | glpshs         | IB                    |
| <i>Astragalus leucolobus</i>                               | Fabaceae       | IL               | PS                  | -0.09   | 2                         | 912.13               | 92.96            | glpshg         | IB                    |
| <i>Astragalus nevadensis</i>                               | Fabaceae       | IL               | PS                  | -0.05   | 2                         | 213.28               | 94.39            | glpshg         | IB                    |
| <i>Astragalus oocarpus</i>                                 | Fabaceae       | IL               | PS                  | 0.08    | NA                        | 896.57               | 91.77            | gspshg         | IB                    |
| <i>Astragalus rattanii</i> var. <i>jepsonianus</i>         | Fabaceae       | MV               | PS                  | -0.28   | 11.05                     | -90.24               | 8.82             | glpshg         | IB                    |
| <i>Atriplex coronata</i> var. <i>vallicola</i>             | Chenopodiaceae | HV               | MV                  | -0.46   | 1.92                      | -98.62               | 0                | glplhg         | IB                    |
| <i>Atriplex coulteri</i>                                   | Chenopodiaceae | HV               | MV                  | -0.54   | 3.69                      | -94.3                | 0.27             | glplhg         | IB                    |
| <i>Atriplex depressa</i>                                   | Chenopodiaceae | HV               | HV                  | -0.42   | 4.18                      | -87.55               | 8.54             | glplhg         | IB                    |
| <i>Atriplex joaquiniana</i>                                | Chenopodiaceae | MV               | MV                  | -0.12   | 5.79                      | -35.7                | 27.03            | glpshg         | IB                    |
| <i>Balsamorhiza macrolepis</i> var. <i>macrolepis</i>      | Asteraceae     | MV               | MV                  | -0.15   | 12.07                     | -12.82               | 40.22            | glplhs         | IB                    |
| <i>Blechnosperma bakeri</i>                                | Asteraceae     | PS               | HV                  | 0.11    | 0.48                      | 224.14               | 99.44            | gspshg         | IB                    |
| <i>Boechera constancei</i>                                 | Brassicaceae   | IL               | PS                  | 0.2     | 16.34                     | 215.52               | 97.21            | gspshs         | IB                    |
| <i>Boechera shockleyi</i>                                  | Brassicaceae   | HV               | HV                  | -0.53   | 18.73                     | -58.99               | 4.02             | glpshs         | 2                     |
| <i>Brodiaea kinkiensis</i>                                 | Themidaceae    | MV               | NA                  | -0.47   | NA                        | -45.12               | 38.66            | gspshg         | IB                    |
| <i>Brodiaea orcuttii</i>                                   | Themidaceae    | HV               | HV                  | -0.22   | 7.06                      | -57.77               | 36.89            | glplhs         | IB                    |
| <i>Californica macrophylla</i>                             | Geraniaceae    | MV               | PS                  | -0.55   | 18.17                     | -33.13               | 2.02             | glpshs         | IB                    |
| <i>Calliandra eriophylla</i>                               | Fabaceae       | HV               | MV                  | -0.62   | 3.51                      | -86.1                | 0                | glpshg         | 2                     |
| <i>Calochortus clavatus</i> var. <i>avicus</i>             | Liliaceae      | MV               | PS                  | -0.6    | 15.04                     | -72.63               | 1.68             | gspshg         | IB                    |
| <i>Calochortus greenii</i>                                 | Liliaceae      | MV               | HV                  | -0.55   | 2.57                      | 28.38                | 16.27            | glplhg         | IB                    |
| <i>Calochortus longebarbatus</i> var. <i>longebarbatus</i> | Liliaceae      | PS               | PS                  | -0.09   | 9.06                      | 45.86                | 69.68            | glplhg         | IB                    |
| <i>Calochortus plummerae</i>                               | Liliaceae      | PS               | HV                  | 0.05    | 18.04                     | 135.12               | 64.99            | glpshs         | 4                     |
| <i>Calochortus pulchellus</i>                              | Liliaceae      | HV               | MV                  | -0.61   | 20.99                     | -100                 | 0                | gspshg         | IB                    |

APPENDIX 1. CONTINUED.

| Taxon                                                          | Family          | CCVI<br>(with D) | CCVI<br>(without D) | Anomaly | Topographic<br>complexity | Range size<br>change | Range<br>overlap | Rarity<br>type | CA Rare<br>Plant Rank |
|----------------------------------------------------------------|-----------------|------------------|---------------------|---------|---------------------------|----------------------|------------------|----------------|-----------------------|
| <i>Calochortus striatus</i>                                    | Liliaceae       | IE               | PS                  | NA      | 10                        | NA                   | NA               | glpsgh         | IB                    |
| <i>Calochortus weedii</i> var. <i>intermedius</i>              | Liliaceae       | PS               | PS                  | 0.35    | 6.66                      | 777.06               | 100              | gspshs         | IB                    |
| <i>Calystegia purpurata</i> subsp. <i>saxicola</i>             | Convolvulaceae  | PS               | PS                  | -0.45   | 1.76                      | 348.29               | 13.93            | glplhg         | IB                    |
| <i>Calystegia stebbinsii</i>                                   | Convolvulaceae  | MV               | MV                  | -0.3    | 15.51                     | 80.63                | 48.19            | glplhs         | IB                    |
| <i>Carex sheldonii</i>                                         | Cyperaceae      | MV               | MV                  | -0.12   | 5.36                      | 60.98                | 59.36            | glplhg         | 2                     |
| <i>Castilleja emoryi</i>                                       | Simarubaceae    | MV               | PS                  | -0.5    | 10.13                     | -95.32               | 3.94             | glplhs         | 2                     |
| <i>Castilleja densiflora</i> subsp. <i>obispoensis</i>         | Orobanchaceae   | PS               | HV                  | -0.04   | 3.59                      | 68.34                | 64.16            | glpsgh         | IB                    |
| <i>Castilleja grisea</i>                                       | Orobanchaceae   | MV               | PS                  | -0.32   | NA                        | -46.31               | 45.01            | gspshg         | IB                    |
| <i>Castilleja lanata</i> subsp. <i>hololeuca</i>               | Orobanchaceae   | MV               | PS                  | -0.38   | NA                        | -73.38               | 14.48            | glpsgh         | IB                    |
| <i>Ceanothus gloriosus</i> var. <i>porrectus</i>               | Rhamnaceae      | MV               | PS                  | -0.17   | 11.13                     | 9.9                  | 45.97            | gspshg         | IB                    |
| <i>Ceanothus purpureus</i>                                     | Rhamnaceae      | IL               | PS                  | 0.11    | 14.55                     | 144.83               | 62.28            | glplhs         | IB                    |
| <i>Centromadia parryi</i> subsp. <i>australis</i>              | Asteraceae      | MV               | HV                  | -0.4    | 2.69                      | 47.89                | 35.71            | glplhg         | IB                    |
| <i>Centromadia parryi</i> subsp. <i>congdonii</i>              | Asteraceae      | HV               | MV                  | -0.58   | 3.82                      | -100                 | 0                | glplhg         | IB                    |
| <i>Chlorogalum grandiflorum</i>                                | Agavaceae       | HV               | MV                  | -0.62   | 14.39                     | -73.18               | 0                | gspshs         | IB                    |
| <i>Chorizanthe polygonoides</i> var. <i>longispina</i>         | Polygonaceae    | HV               | MV                  | -0.36   | 7.81                      | -66.91               | 23.6             | glplhs         | IB                    |
| <i>Cirsium andrewsii</i>                                       | Asteraceae      | PS               | MV                  | 0.08    | 14.78                     | 103.46               | 90.99            | glpsgh         | IB                    |
| <i>Cirsium fontinale</i> var. <i>campylon</i>                  | Asteraceae      | HV               | MV                  | -0.59   | 14.41                     | -92.19               | 3.1              | gspshs         | IB                    |
| <i>Cirsium hydrophilum</i> var. <i>vaseyi</i>                  | Asteraceae      | IL               | PS                  | 0.21    | 17.48                     | 219.32               | 98.53            | gspshs         | IB                    |
| <i>Clarkia borealis</i> subsp. <i>borealis</i>                 | Onagraceae      | IL               | PS                  | -0.14   | 24.89                     | 283.63               | 99.68            | gspshg         | IB                    |
| <i>Clarkia gracilis</i> subsp. <i>albicaulis</i>               | Onagraceae      | MV               | PS                  | -0.1    | 20.41                     | -1.32                | 4.67             | glplhs         | IB                    |
| <i>Clarkia mildrediae</i> subsp. <i>mildrediae</i>             | Onagraceae      | MV               | PS                  | -0.52   | 27.34                     | -46.22               | 0.64             | gspshs         | IB                    |
| <i>Clarkia mosquinii</i>                                       | Onagraceae      | IL               | PS                  | 0.22    | 23.87                     | 842.67               | 100              | gspshg         | IB                    |
| <i>Clarkia rostrata</i>                                        | Onagraceae      | MV               | PS                  | -0.54   | 12.05                     | -78.14               | 0.02             | glplhg         | IB                    |
| <i>Conarostaphylis diversifolia</i> subsp. <i>diversifolia</i> | Ericaceae       | MV               | MV                  | -0.47   | 13.36                     | -56.44               | 2.91             | glpsgh         | IB                    |
| <i>Coptis laciniata</i>                                        | Ranunculaceae   | MV               | MV                  | -0.51   | 19.43                     | -85.03               | 13.6             | glplhg         | 2                     |
| <i>Corethrogyne filaginifolia</i> var. <i>linifolia</i>        | Asteraceae      | MV               | MV                  | -0.17   | 8.61                      | -18.55               | 48.86            | gspshg         | IB                    |
| <i>Cymopterus gilmanii</i>                                     | Apiaceae        | HV               | HV                  | 0.23    | 21.24                     | -49.55               | 30.96            | glpsgh         | 2                     |
| <i>Deinandra conjugens</i>                                     | Asteraceae      | PS               | MV                  | 0.38    | 8.5                       | 536.77               | 99.64            | glplhg         | IB                    |
| <i>Delphinium hutchinsoniae</i>                                | Ranunculaceae   | HV               | MV                  | -0.57   | 24.74                     | -100                 | 0                | glpsgh         | IB                    |
| <i>Delphinium recurvatum</i>                                   | Ranunculaceae   | MV               | PS                  | -0.34   | 2.52                      | -87.64               | 2.64             | glplhg         | IB                    |
| <i>Dudleya abramsii</i> subsp. <i>setchellii</i>               | Crassulaceae    | HV               | MV                  | -0.6    | 16.71                     | -92.76               | 0.07             | gspshs         | IB                    |
| <i>Dudleya blochmaniae</i> subsp. <i>blochmaniae</i>           | Crassulaceae    | HV               | MV                  | -0.25   | 8.79                      | -64.43               | 26.36            | glplhs         | IB                    |
| <i>Dudleya parva</i>                                           | Crassulaceae    | IE               | HV                  | NA      | 19.14                     | NA                   | NA               | glplhs         | IB                    |
| <i>Epilobium oreganum</i>                                      | Onagraceae      | MV               | PS                  | -0.35   | 14.24                     | -89.09               | 10.74            | glpsghs        | IB                    |
| <i>Eremogone cliffonii</i>                                     | Caryophyllaceae | MV               | PS                  | -0.17   | 18.94                     | 19.94                | 23.45            | glplhs         | IB                    |
| <i>Eremogone ursina</i>                                        | Caryophyllaceae | HV               | MV                  | -0.6    | 8.82                      | -65.31               | 0.03             | glpsgh         | IB                    |
| <i>Eriogonum giganteum</i> var. <i>formosum</i>                | Polygonaceae    | MV               | PS                  | -0.31   | NA                        | -34.69               | 44.05            | gspshg         | IB                    |
| <i>Eriogonum twisselhamii</i>                                  | Polygonaceae    | MV               | MV                  | -0.53   | 27.32                     | 120.23               | 15.36            | gspshs         | IB                    |
| <i>Eryngium spinosepalum</i>                                   | Apiaceae        | MV               | PS                  | -0.31   | 20.28                     | -60.4                | 25.05            | glplhg         | IB                    |
| <i>Erythronium revolutum</i>                                   | Liliaceae       | PS               | MV                  | 0.01    | 2.55                      | 447.4                | 96.34            | glplhg         | 2                     |
| <i>Fritillaria eastwoodiae</i>                                 | Liliaceae       | MV               | PS                  | -0.17   | 14.77                     | 102.85               | 50.43            | glpsghs        | 3                     |
| <i>Fritillaria lanceolata</i> var. <i>tristulis</i>            | Liliaceae       | IL               | PS                  | 0.13    | 12.29                     | 224.42               | 95.61            | glpsghs        | IB                    |
| <i>Fritillaria liliacea</i>                                    | Liliaceae       | MV               | MV                  | -0.14   | 9.34                      | -18.5                | 34.92            | glplhs         | IB                    |

| Taxon                                                | Family           | CCVI<br>(with D) | CCVI<br>(without D) | Anomaly | Topographic<br>complexity | Range size<br>change | Range<br>overlap | Rarity<br>type | CA Rare<br>Plant Rank |
|------------------------------------------------------|------------------|------------------|---------------------|---------|---------------------------|----------------------|------------------|----------------|-----------------------|
| <i>Fritillaria pluriflora</i>                        | Liliaceae        | IL               | PS                  | 0.29    | 8.81                      | 534.69               | 99.56            | gplhs          | 1B                    |
| <i>Galium californicum</i> subsp. <i>sierrae</i>     | Rubiaceae        | HV               | MV                  | -0.37   | 9.71                      | -11.08               | 10.24            | gsplhs         | 1B                    |
| <i>Galium catalinense</i> subsp. <i>acrispium</i>    | Rubiaceae        | PS               | PS                  | -0.21   | NA                        | 5.38                 | 69.1             | gspshg         | 1B                    |
| <i>Galium serpenticum</i> subsp. <i>scotticum</i>    | Rubiaceae        | MV               | PS                  | -0.59   | 23.11                     | -89.14               | 0.63             | gplhs          | 1B                    |
| <i>Gilia capitata</i> subsp. <i>chamissonis</i>      | Polemoniaceae    | MV               | MV                  | NA      | 9.14                      | NA                   | NA               | gplgh          | 1B                    |
| <i>Gilia capitata</i> subsp. <i>pacifica</i>         | Polemoniaceae    | PS               | PS                  | -0.12   | 15.7                      | -36.27               | 60.29            | gplgh          | 1B                    |
| <i>Gilmania luteola</i>                              | Polygonaceae     | PS               | MV                  | 0.14    | 10.93                     | 238.24               | 72.79            | gplshg         | 1B                    |
| <i>Gratiola heterosepala</i>                         | Plantaginaceae   | MV               | MV                  | -0.13   | 1.79                      | 80.04                | 55.28            | gplgh          | 1B                    |
| <i>Hazardia cana</i>                                 | Asteraceae       | MV               | PS                  | -0.34   | NA                        | -68.95               | 26.2             | gspshg         | 1B                    |
| <i>Hesperex sparsiflora</i> var. <i>brevifolia</i>   | Asteraceae       | IE               | PS                  | NA      | NA                        | NA                   | NA               | gsplhs         | 1B                    |
| <i>Hesperolinon bicarpellatum</i>                    | Linaceae         | IL               | PS                  | 0.37    | 14.24                     | 1760.49              | 99.99            | gplhs          | 1B                    |
| <i>Hesperolinon breweri</i>                          | Linaceae         | HV               | MV                  | -0.63   | 19.09                     | -92.97               | 0.03             | gplhs          | 1B                    |
| <i>Hesperolinon congestum</i>                        | Linaceae         | PS               | MV                  | 0.23    | 11.55                     | 193.2                | 98.58            | gsplhs         | 1B                    |
| " <i>Hesperolinon serpentinum</i> "                  | Linaceae         | IE               | PS                  | NA      | 8.27                      | NA                   | NA               | gplgh          | 1B                    |
| <i>Heuchera hirsutissima</i>                         | Saxifragaceae    | HV               | MV                  | -0.47   | 31.47                     | -95.67               | 0.42             | gplshs         | 1B                    |
| <i>Horkelia parryi</i>                               | Rosaceae         | MV               | PS                  | -0.57   | 9.71                      | -73.03               | 0.11             | gplhs          | 1B                    |
| <i>Ilamma bakeri</i>                                 | Malvaceae        | PS               | MV                  | 0.28    | 0.6                       | 2093.41              | 100              | gspshg         | 4                     |
| <i>Isocoma arguta</i>                                | Asteraceae       | HV               | MV                  | -0.56   | 9.03                      | -55.39               | 0                | gspshg         | 1B                    |
| <i>Ivesia argyrocoma</i> var. <i>argyrocoma</i>      | Rosaceae         | MV               | MV                  | -0.21   | 2.14                      | 130.04               | 59.44            | gplhs          | 1B                    |
| <i>Ivesia sericoleuca</i>                            | Rosaceae         | PS               | MV                  | 0.27    | 1.86                      | 473.82               | 100              | gspshg         | 1B                    |
| <i>Juncus leiostermus</i> var. <i>leiostermus</i>    | Juncaceae        | MV               | PS                  | -0.36   | 10.68                     | -27.6                | 32.73            | gplgh          | 1B                    |
| <i>Layia heterotricha</i>                            | Asteraceae       | PS               | HV                  | 0.09    | 13.61                     | 191.83               | 72.8             | gplshg         | 1B                    |
| <i>Lepidium virginicum</i> var. <i>robinsonii</i>    | Brassicaceae     | HV               | MV                  | -0.6    | 16.56                     | -90.55               | 0                | gplhs          | 1B                    |
| <i>Lessingia micradenia</i> var. <i>glabrata</i>     | Asteraceae       | PS               | PS                  | -0.26   | 35.35                     | 79.78                | 58.78            | gsplhs         | 1B                    |
| <i>Lewisia cantelovii</i>                            | Montiaceae       | HV               | MV                  | -0.54   | 5.79                      | -100                 | 0                | gplshg         | 1B                    |
| <i>Lilium maritimum</i>                              | Liliaceae        | HV               | MV                  | -0.46   | 20.46                     | -73.9                | 11.96            | gplshg         | 1B                    |
| <i>Lilium parryi</i>                                 | Liliaceae        | PS               | PS                  | -0.1    | 2.94                      | 48.86                | 88.02            | gspshg         | 1B                    |
| <i>Limnanthes bakeri</i>                             | Limnanthaceae    | HV               | HV                  | -0.58   | 0.51                      | -74.57               | 9.24             | gspshg         | 2                     |
| <i>Limnanthes vincularis</i>                         | Limnanthaceae    | PS               | MV                  | 0.05    | 1.34                      | 189.22               | 99.12            | gspshg         | 1B                    |
| <i>Limosella australis</i> *                         | Scrophulariaceae | MV               | MV                  | -0.23   | 10.01                     | -26.14               | 69.1             | gplgh          | 2                     |
| <i>Loeflingia squarrosa</i> var. <i>artemisiarum</i> | Caryophyllaceae  | PS               | MV                  | -0.29   | 1.36                      | 91.98                | 65.3             | gplgh          | 2                     |
| <i>Lonium stebbinsii</i>                             | Apiaceae         | PS               | MV                  | 0.15    | 12.3                      | 314.06               | 87.31            | gsplhs         | 1B                    |
| <i>Lotus nuttallianus</i>                            | Fabaceae         | PS               | HV                  | 0.37    | 1.26                      | 284.9                | 97.25            | gspshg         | 1B                    |
| <i>Lycopodium clavatum</i>                           | Lycopodiaceae    | MV               | MV                  | -0.52   | 13.84                     | -76.28               | 21.76            | gplshg         | 4                     |
| <i>Malacothamnus abbotii</i>                         | Malvaceae        | MV               | MV                  | -0.51   | 9.17                      | -53.13               | 40.52            | gspshg         | 1B                    |
| <i>Malacothamnus hallii</i>                          | Malvaceae        | HV               | MV                  | -0.59   | 15.67                     | -99.79               | 0                | gplhs          | 1B                    |
| <i>Microseris paludosa</i>                           | Asteraceae       | PS               | PS                  | -0.09   | 6.81                      | -6.28                | 55.98            | gplshg         | 1B                    |
| <i>Minulus fremontii</i> var. <i>vandenbergensis</i> | Phrymaceae       | HV               | MV                  | -0.39   | 7.87                      | -86.14               | 12.83            | gspshg         | 1B                    |
| <i>Minulus purpureus</i>                             | Phrymaceae       | EV               | HV                  | -0.76   | 4.91                      | -62.01               | 0                | gplgh          | 1B                    |
| <i>Monardella hypoleuca</i> subsp. <i>lanata</i>     | Lamiaceae        | MV               | EV                  | -0.04   | 3.7                       | 247.14               | 98.47            | gplgh          | 1B                    |
| <i>Monardella stebbinsii</i>                         | Lamiaceae        | HV               | MV                  | -0.41   | 16.07                     | -93.63               | 4                | gplgh          | 1B                    |
| <i>Monolopia congdonii</i>                           | Asteraceae       | PS               | MV                  | 0.15    | 37.36                     | 261.98               | 100              | gspshs         | 1B                    |
| <i>Munzothamnus blairii</i>                          | Asteraceae       | MV               | PS                  | -0.28   | NA                        | -53.06               | 37               | gspshg         | 1B                    |



APPENDIX 1. CONTINUED.

| Taxon                                                | Family          | CCVI<br>(with D) | CCVI<br>(without D) | Anomaly | Topographic<br>complexity | Range size<br>change | Range<br>overlap | Rarity<br>type | CA Rare<br>Plant Rank |
|------------------------------------------------------|-----------------|------------------|---------------------|---------|---------------------------|----------------------|------------------|----------------|-----------------------|
| <i>Orcuttia viscida</i>                              | Poaceae         | HV               | EV                  | 0.25    | 0.95                      | 754.92               | 100              | gspshg         | 1B                    |
| <i>Packera eurycephala</i> var. <i>lewisrosei</i>    | Asteraceae      | MV               | MV                  | 0.08    | 25.51                     | 472.34               | 75.63            | gspshs         | 1B                    |
| <i>Packera layneae</i>                               | Asteraceae      | HV               | MV                  | -0.61   | 10.8                      | -11.2                | 0.14             | gspshs         | 1B                    |
| <i>Penstemon californicus</i>                        | Plantaginaceae  | MV               | MV                  | -0.17   | 11.95                     | -57.7                | 21.87            | gplshg         | 1B                    |
| <i>Penstemon filiformis</i>                          | Plantaginaceae  | IL               | PS                  | -0.36   | 16.09                     | 111.94               | 51.72            | gplshs         | 1B                    |
| <i>Penstemon sudans</i>                              | Plantaginaceae  | MV               | MV                  | -0.29   | 12.9                      | 34.72                | 75.15            | gspshg         | 1B                    |
| <i>Phacelia argentea</i>                             | Boraginaceae    | IE               | HV                  | NA      | 2.26                      | NA                   | NA               | gspshg         | 1B                    |
| <i>Phacelia nashiana</i>                             | Boraginaceae    | MV               | MV                  | -0.5    | 22.58                     | 1.42                 | 2.5              | gspshs         | 1B                    |
| <i>Phacelia novemmillensis</i>                       | Boraginaceae    | MV               | MV                  | -0.51   | 25.54                     | 107.47               | 17.43            | gspshg         | 1B                    |
| <i>Phlox muscoides</i>                               | Polemoniaceae   | MV               | PS                  | -0.51   | 12.05                     | -99.13               | 0.83             | gspshg         | 2                     |
| <i>Piperia candida</i>                               | Orchidaceae     | MV               | PS                  | -0.16   | 20.57                     | -30.99               | 56.98            | gplshs         | 1B                    |
| <i>Piperia yadonii</i>                               | Orchidaceae     | EV               | HV                  | -0.52   | 8.97                      | -100                 | 0                | gspshg         | 1B                    |
| <i>Plagiobothrys hystriculus</i>                     | Boraginaceae    | PS               | HV                  | 0.26    | 0.26                      | 2617.31              | 100              | gspshg         | 1B                    |
| <i>Pogogyne abramsii</i>                             | Lamiaceae       | MV               | EV                  | -0.2    | 2.98                      | 305.14               | 76.43            | gplshg         | 1B                    |
| <i>Prunus erenophila</i>                             | Rosaceae        | PS               | HV                  | 0.27    | 3.14                      | 171.11               | 99.48            | gspshs         | 1B                    |
| <i>Pyrocoma lucida</i>                               | Asteraceae      | PS               | MV                  | -0.26   | 2.76                      | 111.83               | 36.65            | gplshg         | 1B                    |
| <i>Rupertia hallii</i>                               | Fabaceae        | HV               | MV                  | -0.68   | 16.8                      | -99.21               | 0                | gspshg         | 1B                    |
| <i>Salvia munzii</i>                                 | Lamiaceae       | MV               | MV                  | 0.14    | 13.86                     | -14.2                | 69.65            | gplshg         | 2                     |
| <i>Sidalcea calycosa</i> subsp. <i>rhizomata</i>     | Malvaceae       | PS               | MV                  | 0.15    | 6.08                      | 92.29                | 96.45            | gplshg         | 1B                    |
| <i>Smilax jamesii</i>                                | Smilacaceae     | MV               | PS                  | -0.5    | 11.39                     | 22.96                | 37.02            | gplshg         | 1B                    |
| <i>Sphaeralcea rusbyi</i> var. <i>eremicola</i>      | Malvaceae       | PS               | MV                  | -0.19   | 8.89                      | 132.39               | 82.33            | gspshs         | 1B                    |
| <i>Stenotus lanuginosus</i>                          | Asteraceae      | HV               | MV                  | -0.57   | 2.96                      | -52.78               | 0.9              | gspshg         | 2                     |
| <i>Streptanthus albidus</i> subsp. <i>peramoenus</i> | Brassicaceae    | HV               | HV                  | -0.53   | 17.7                      | -99.95               | 0.03             | gplshs         | 1B                    |
| <i>Streptanthus morrisonii</i>                       | Brassicaceae    | IL               | PS                  | 0.22    | 17.71                     | 602.34               | 99.89            | gplshs         | 1B                    |
| <i>Symphylorichum lentum</i>                         | Asteraceae      | HV               | EV                  | -0.58   | 0.61                      | -39.16               | 2.01             | gplshg         | 1B                    |
| <i>Taraxacum californicum</i>                        | Asteraceae      | HV               | MV                  | -0.64   | 7.59                      | -67                  | 0                | gspshg         | 1B                    |
| <i>Tetracoccus dioicus</i>                           | Picrodendraceae | HV               | HV                  | -0.29   | 15.41                     | -59.52               | 35.55            | gplshs         | 1B                    |
| <i>Thermopsis robusta</i>                            | Fabaceae        | MV               | PS                  | -0.47   | 18.41                     | -85.05               | 6.07             | gplshs         | 1B                    |
| <i>Thysanocarpus conculiferus</i>                    | Brassicaceae    | MV               | PS                  | -0.55   | NA                        | -67.57               | 5.54             | gspshg         | 1B                    |
| <i>Trifolium polyodon</i>                            | Fabaceae        | PS               | PS                  | -0.3    | NA                        | 40.95                | 88.69            | gspshg         | 1B                    |
| <i>Triphysaria floribunda</i>                        | Orobanchaceae   | HV               | HV                  | -0.28   | 9.11                      | -36.31               | 33.19            | gplshs         | 1B                    |
| <i>Triteleia clementina</i>                          | Themidaceae     | IE               | MV                  | NA      | 7.84                      | NA                   | NA               | gspshg         | 1B                    |
| <i>Verbena californica</i>                           | Verbenaceae     | MV               | HV                  | -0.53   | 8.29                      | 29.66                | 3.29             | gspshs         | 1B                    |
| <i>Wyethia reticulata</i>                            | Asteraceae      | HV               | PS                  | -0.44   | 9.71                      | -78.23               | 0                | gspshs         | 1B                    |
| <i>Xylorhiza orcuttii</i>                            | Asteraceae      | MV               | MV                  | NA      | 6.57                      | NA                   | NA               | gplshg         | 1B                    |